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Bang or Bounce

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Abstract

Following up an earlier suggestion of how the Tolman Entropy Conundrum (TEC) can be solved in a cyclic cosmology using the Come Back Empty (CBE) assumption with phantom dark energy, here we show how the same CBE strategy may work with a cosmological constant in the expansion era. As in the earlier case, this leads to a multiverse, actually an infiniverse, with the concomitant issues of predictivity and testability. Here we show how extreme flatness and homogeneity at the bounce are natural properties of the contraction era, interestingly without any necessity for an inflationary era at the beginning of the present expansion. Essential ingredients in the solution of TEC are CBE contraction and a careful treatment of what is meant by the visible universe.

Introduction. It is of broad interest to understand better the nature of the early universe especially the big bang. The discovery [1] of the cosmic microwave background(CMB) in 1965 resolved a dichotomy then existing in theoretical cosmology between steady-state and big bang theories. The interpretation of the CMB as a relic of a big bang was compelling and the steady-state theory died. Actually at that time it was really a trichotomy being reduced to a dichotomy because a third theory, a bounce in a cyclic cosmology had been under study since 1922 [2].

Nevertheless, for purely theoretical reasons, the bounce had been discarded due to the Tolman Entropy Conundrum(TEC) [3,4]. The TEC, stated simply, is that the entropy of the universe necessarily increases, due to the second law of thermodynamics, and therefore cycles become larger and longer in the future, smaller and shorter in the past, implying that a big bang must have occurred at a finite time in the past.

Some progress towards a solution of the TEC was made in [5] using the Come Back Empty (CBE) assumption in the BF model. A huge entropy was there jettisoned at turnaround and the significantly smaller universe, empty of matter, contracted adiabatically to a bounce with zero entropy. The BF model employed so-called phantom dark energy with equation of state $\omega < -1$. Since this violates energy conditions, it is more conservative to use a cosmological constant with $\omega = -1$ as we do here. We shall find CBE is still possible.

Assuming the cosmological principle of homogeneity and isotropy leads to the FLRW metric

$$ds^2 = dt^2 - a(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right] \quad (1)$$

where $a(t)$ is the scale factor and k the curvature. Inserting this metric into the Einstein equation leads to two Friedmann equations. The first is the expansion equation

$$H(t)^2 = \left(\frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G}{3} \rho_{TOT}(t) - \frac{k}{a(t)^2} \quad (2)$$

where $\rho_{TOT}(t)$ is the total density.

Using the continuity equation $\dot{\rho} + 3H(\rho + p) = 0$, differentiation gives rise to a second equation

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho + 3p) \quad (3)$$

The critical density is defined by $\rho_c(t) = [3H(t)^2/8\pi G]$ and discussion of flatness involves proximity to one of the quantity

$$\Omega_{TOT}(t) = \frac{\rho_{TOT}}{\rho_c(t)} \quad (4)$$

Let the present time be $t = t_0 = 1.38 \times 10^{10}$ y. Normalize $a(t_0) = 1$ and define $H(t_0) = H_0$. Other relevant times all measured relative to the would-have-been bang at $t = 0$ are the Planck time $t_{Planck} = 10^{-44}$ s, the electroweak time $t_{EW} = 10^{-10}$ s, the onset of matter domination $t_m = 4.7 \times 10^4$ y, the onset of dark energy domination $t_{DE} = 9.8$ Gy and for the turnaround time we shall use $t_T = t_0 + 150 = 163.8$ Gy. The bounce occurs at t_B where $t_{Planck} < t_B < t_{EW}$.

In the unadorned big bang theory, one has dependences of the scale factor $a(t) \sim t^{1/2}$ for $t_{Planck} < t < t_m$, $a(t) \sim t^{2/3}$ for $4t_m < t < t_{DE}$, and $a(t) = \exp[H_0(t - t_0)]$ for $t_{DE} < t < t_T$. This leads to the values of $a(t)$ to be used later: $a(t_{Planck}) = 2.3 \times 10^{-32}$, $a(t_{EW}) = 2.3 \times 10^{-15}$, $a(t_m) = 2.8 \times 10^{-4}$, $a(t_{DE}) = 0.75$, $a(t_0) = 1$, and $a(t_T) = 5.7 \times 10^4$.

Two of the most striking observations of the universe are isotropy to an accuracy $1 \pm O(10^{-5})$ and flatness $\Omega_{TOT}(t_0) = 1.00 \pm 0.05$. In big bang theory this implies that in the early universe $\Omega_{TOT}(t)$ is given by

$$\Omega_{TOT}(t_{EW}) = 1 \pm O(10^{-27}) \quad (5)$$

$$\Omega_{TOT}(t_{Planck}) = 1 \pm O(10^{-61}) \quad (6)$$

Inflation. A simple way to present inflation is to rearrange Eq.(2) after division by $H(t)^2$ as

$$(\Omega_{TOT}(t) - 1) = \frac{k}{\dot{a}(t)^2} \quad (7)$$

In a decelerating expansion the denominator of the RHS in Eq.(7) becomes small and $\Omega_{TOT}(t)$ deviates more and more from $\Omega_{TOT}(t) = 1$. This is why the proximity of $[\Omega_{TOT}(t_0) - 1]$ to zero imposes the strong initial conditions in Eqs.(5) and (6).

The most popular explanation of flatness is inflation [6] which inserts a period of highly accelerated superluminal expansion at time $t = t_{inflation}$ during the period $t_{Planck} < t_{inflation} < t_{EW}$. While inflating, $\dot{a}(t)$ becomes extremely large enforcing flatness so precisely that the subsequent decelerating expansion during $t_{inflation} < t < t_{DE}$ does not remove it.

Inflation also explains homogeneity and has other successes including the prediction of scale-invariant density perturbations and of the reddening spectral index. Inflation has been incorporated into string theory [8, 9]. The successful discovery of the BEH boson adds credibility to the existence of the scalar inflaton. One possible objection to inflation, that it leads to eternal inflation [10] and hence to a multiverse in which predictivity is hampered by the measure problem [11], is not a fatal flaw.

Thus, only a compelling alternative could cast doubt on the correctness of inflation.

Turnaround. To solve the TEC, the entropy of the visible universe must essentially vanish as discussed in [5]. As given above, the scale factor at turnaround is $a(t_T) = 5.7 \times 10^4$ at $t_T = 163.8\text{Gy}$. At the present time the visible universe has radius $R_{VU} = 4.4 \times 10^{26}\text{m}$. For $t = t_T$, this evolves to $R_{VU}(t_T) \simeq R_{VU}(\infty) = R_{VU}(t_0) + cH_0^{-1} = 5.7 \times 10^{26}\text{m}$ due to the exponential expansion.

Because of the superluminal expansion of space $R_{VU}(t_0)$ is meanwhile stretched to the much larger radius $a(t_T)R_{VU}(t_0) = 2.5 \times 10^{31}\text{m}$. Assuming 10^{12} galaxies inside $R_{VU}(t_0)$ a typical intergalactic(IG) distance is $d_{IG}(t_0) = 10^{-4}R_{VU}(t_0) = 2.2 \times 10^{22}\text{m}$ which will be stretched to $d_{IG}(t_T) = a(t_T)d_{IG}(t_0) = 2.5 \times 10^{27}\text{m}$ that is greater than $R_{VU}(t_T)$. This implies that a visible universe at turnaround contains zero or one galaxies.

It now requires great care to identify the appropriate visible universe at turnaround to fulfill the CBE assumption. One might be tempted to include the galaxy we live in but that would be too Ptolemaic, The correct choice of $R_{VU}(t_T)$ is instead a sphere which contains no matter, luminous or dark, and no black holes. It contains instead only dark energy with no entropy and an infinitesimal quantity of both curvature and radiation, this last necessary for the ensuing derivation of flatness.

In the language of [5], an important ratio (f) of the contraction to expansion scale factors in $\hat{a}(t) = fa(t)$ is here given by

$$f = \frac{R_{VU}(t_T)}{a(t_T)R_{VU}(t_0)} = 2.3 \times 10^{-5} \quad (8)$$

Bounce. The CBE contracting universe contains no matter. It does, however, contain a crucial infinitesimal amount of radiation so that approaching the bounce $\Omega_{TOT}(t) = \Omega_\gamma(t)$. During the expansion era at $t = t_0$ its contribution is $\Omega_\gamma(t_0) = 1.3 \times 10^{-4}$.

The contraction Friedmann equation is, from Eq.(3) and using the radiation equation of state $3p = \rho$

$$\frac{\ddot{\hat{a}}(t)}{\dot{\hat{a}}(t)} = -\frac{8\pi G}{3}\rho_\gamma(t) \quad (9)$$

and we need to calculate $\dot{\hat{a}}(t_B)$ which appears in this contraction version of Eq.(7)

$$|\Omega_{TOT}(t_B) - 1| = \left| \frac{k}{\dot{\hat{a}}(t_B)^2} \right| \quad (10)$$

Integrating Eq.(9) and using $\rho_\gamma(t) = \rho_{\gamma 0}/\hat{a}(t)^4$ gives the following results for flatness at $t = t_{EW}$ and t_{Planck}

$$|\Omega_{TOT}(t_B) - 1| = 3.5 \times 10^{-46} \quad (t_B = t_{EW}) \quad (11)$$

$$|\Omega_{TOT}(t_B) - 1| = 3.5 \times 10^{-80} \quad (t_B = t_{Planck}) \quad (12)$$

which is our main result.

This extreme flatness is not surprising because it is suppressed by the CBE factor $f^4 \sim 10^{-18}$ relative to the expanding phase together with the stability of $\Omega_{TOT}(t) = 1$ under contraction, behaving precisely oppositely to the fine tunings of Eqs(5) and (6). Homogeneity at the bounce is ensured by its essentially zero entropy.

Thus, this provides an alternative explanation for the observed isotropy and flatness which can now be regarded as evidence not for inflation but for a bounce.

Discussion. In order to construct a cyclic cosmology, a first requirement is to address the TEC which was an impossible-seeming hurdle and which discouraged workers in the 1920s who were otherwise very enthusiastic about this alternative to the big bang. The only logical possibility is that a huge entropy must be jettisoned at turnaround.

It is interesting that TEC+CBE necessitates an accelerated expansion just as was first discovered in 1998. With decelerated expansion the fraction $f < 1$ necessary for the CBE assumption is not possible. The advantages of a bounce over a bang are that the low entropy at the bounce ensures homogeneity and that the appropriate degree of flatness is obtained naturally, interestingly without the necessity of an inflation at the beginning of the expansion era. It is almost inevitable that inflation will lead to eternal inflation as explained in [10] and to a multiverse with its measure problem [11]. Similarly this TEC+CBE model, just as in [5], will almost inevitably lead to an infiniverse; after all, the entropy at turnaround must go elsewhere.

One prediction is that, because of the additional factor f^4 , the flatness condition at the present time is $\Omega(t_0) = 1$, accurate to some eighteen decimal places. Predictions for density perturbations and the spectral index are to be investigated in future research.

Finally it is worth remarking that in his monumental work [3,4], Tolman did not consider accelerated expansion and, to my knowledge, never entertained the possibility of more than one universe.

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